THEORY OF THE FLAME HOLDER

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THEORY OF THE FLAME HOLDER

By

Jennings Pemble Field, Jr.
Lieutenant Commander, U.S.N.

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Acknowledgment

The writer owes a debt of gratitude to Professor Neil F. Bailey for his helpful suggestions in planning and carrying out this investigation.

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THEORY OF THE FLAME HOLDER

Introduction

Flame Holders. A flame holder is a device for holding a flame in a rapidly flowing free stream of gas, and thereby making it possible to burn in a stream of much higher velocity than it would otherwise be possible to burn in.

The ability to burn effectively in high velocity streams has lately become tremendously important because of the growing use of all types of jet propulsion mechanisms in which most of the burning occurs in fairly high velocity streams. This problem is relatively new because in conventional gasoline or diesel engines the stream velocity is effectively zero and the type of burning encountered there is entirely different from that in a flowing stream. A clear distinction is to be made between a flame holder and a turbojet combustor: the turbojet combustor is a device used to burn in a constrained flow requiring all the gas to pass through the combustor whereas the flame holder is inserted into the stream and disturbs it as little as possible while still maintaining combustion; fuel is always injected through the combustor but fuel may be injected either in or upstream from a flame holder.

A great deal of work has undoubtedly been done on this problem by the U.S.Navy, the U.S.Army, and many industrial companies working under contract to them or on private projects; but by reason of its military and economic aspects practically nothing has been published about the fundamental nature of the process of flame holding.

In fact, it is not well known generally which types of flame holders are now in greatest use and which types have been found unsuitable; because most of the ones in use are employed in military ram jets, the details of which cannot be divulged. Although this investigator is a member of the armed services, no classified information has been drawn upon and the problem has been attacked on the basis of information available in the public scientific literature only.

So far as is known most of the investigations on flame holders have been little more than trial and error investigations with little or no attempt to discover the exact mechanism by which the device holds the flame. It is generally stated[1] that the flame holder, which usually has a concave downstream surface, does its work by creating a turbulent wake where combustion occurs more readily than in the adjoining free flowing stream, and that this burning turbulent region acts as a source of continuous ignition for the main stream. A simplified drawing of a hypothetical flame holder showing the assumed path of the air particles and the way in which the flame spreads is shown in figure 1. According to Dr. Nerad the incoming gas "rolls through the flame" and is preheated to about 1500° F in a manner very similar to the action in a turbojet combustor. However, no quantitative measures of flame holder effectiveness are in use, no quantitative predictions for the performance of a given size or shape are made, and in general it is not known what relations exist between size, shape,

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1. After a description given by Dr. Nerad of the General Electric Company before the jet propulsion students at Rensselaer Polytechnic Institute in March 1947.

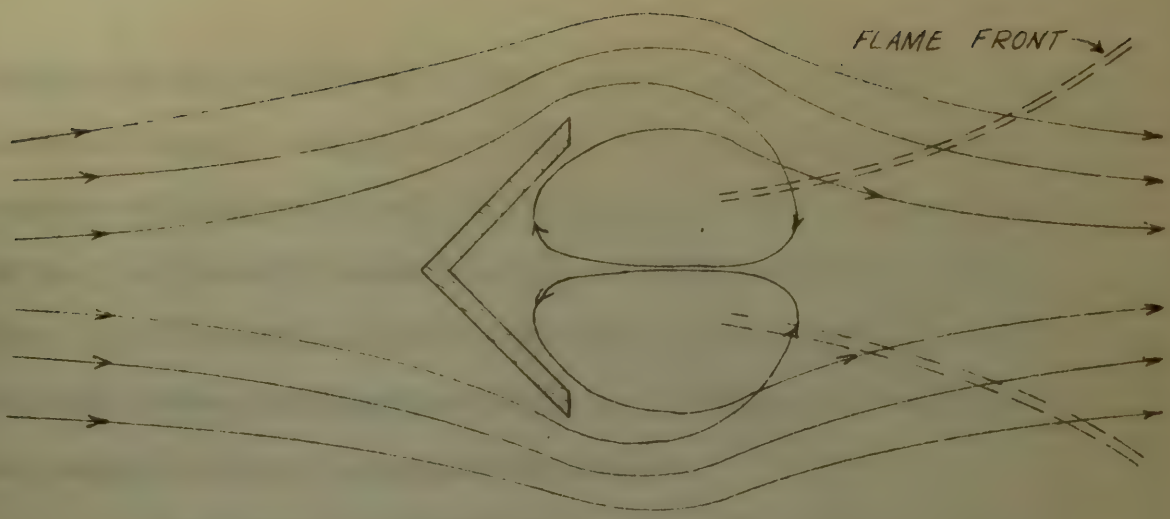

FIG. 1

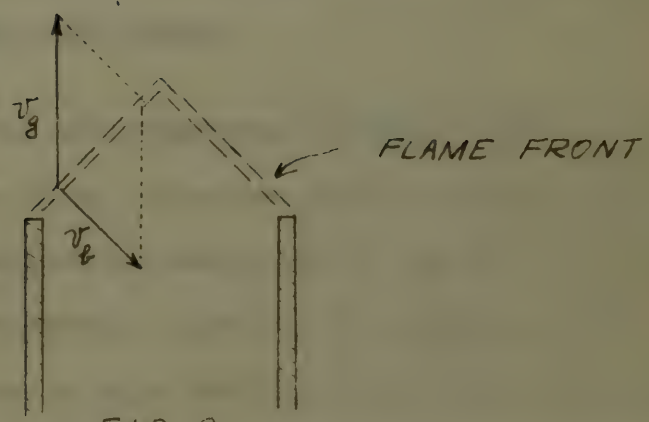

FIG 2

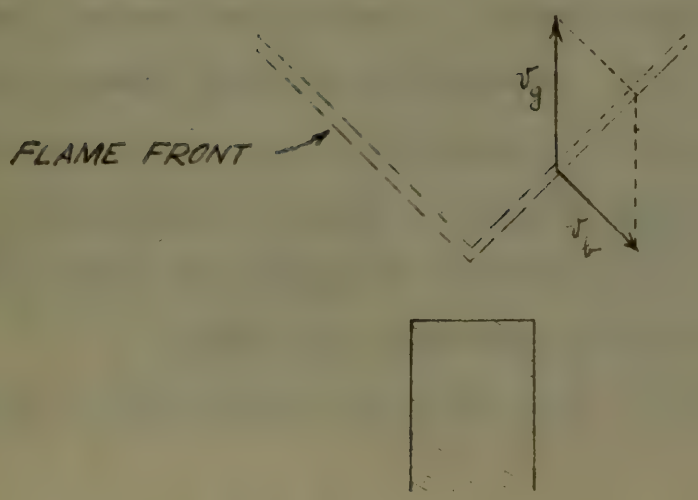

FIG 3

stream velocity, stream turbulence, and the other variables, of which there are legion. Perhaps the nearest fairly common approach to a measure of the effectiveness of a given flame holder is the reporting of the loss in total pressure across it in the stream, but this implies that the total amount of turbulence is the significant characteristic rather than the distribution or arrangement of the turbulence, an assumption with no apparent justification.

The purpose of this investigation is to discover the fundamental mechanism by which a flame holder holds a flame. Once these significant variables are determined and the effect of each is understood, a basis for design will exist.

Combustion Studies. The most fundamental studies of flame mechanisms are found in the work of those scientists who have investigated the process of burning in the Bunsen burner, and it was from the work of these people that the theoretical basis for this work was taken. Among the outstanding men in this field whose work was consulted are: F. A. Smith, S. F. Pickering, H. Mache, Wilhelm Jost, and most important of all, Bernard Lewis of the U. S. Bureau of Mines and Guenther von Elbe of the Carnegie Institute of Technology. The latter two workers, in particular have made notable advances in understanding the mechanism of combustion and have given a functional picture of the Bunsen burner process which for accuracy and detail is truly remarkable.

In a burning gas, combustion occurs in a narrow zone separating the unburned from the burned gases. This zone is a region of

intense chemical reaction which propagates itself as a Huygens wave in a direction normal to its surface. The velocity of propagation with respect to the stationary unburned air, called the "burning velocity", is controlled by the rate at which the chemical reactions are induced in successive gas layers by (1) diffusion of active species such as H, OH, HO_2, O, and CHO into the unburned gas, and (2) heat transfer into the unburned gas, mainly by conduction. The burning velocity in a still gas for most normal gaseous fuels is in the neighborhood of two to five feet per second, a figure far below that essential for combustion in a high velocity stream. A flame remains stationary in a moving stream, as in a burner, only because there are regions in which the flame velocity is equal to the local stream velocity, such regions usually being near the rim or near an obstruction in the stream such as the grid of a Meker burner. The burning regions continuously ignite the remainder of the gas as it flows by, the flame spreading out from these centers in such a way that the normal component of the gas velocity equals the burning velocity. This gives rise to a cone in the case of the Bunsen burner (Fig. 2) and to an inverted cone in the case of the simple flame holder (Fig. 3). This has been well understood for years and the angle formed by the vertex of the cone, together with the known velocity of the stream, has been used to determine the burning velocities of the fuels.

The new contribution of Lewis and von Elbe is a detailed explanation of how the regions of equality of gas velocity and burning velocity are established in the process of burning. The two

predominating influences are: (1) friction, which slows down the gas velocity near the solid wall, and (2) inhibition of the explosive reaction by the wall by means of (a) destruction of the chain carriers and (b) cooling. Thus the wall decreases both the gas velocity and the burning velocity. There is always a layer of one molecule thickness at rest on the wall and the gas velocity increases with the distance from the wall in a manner dependent for a given gas primarily upon the velocity and degree of turbulence of the flow. The burning velocity is also zero at the wall and for a short distance from the wall after which it increases gradually until at a certain distance the wall has no further effect and the burning velocity is a function of the fuel mixture, degree of turbulence, amount of preheating, and other variables. This can be seen in the phenomenon of flash-back where the flame progresses down the tube against the flow with the fringes trailing the central portion and not making contact with the wall itself. In ordinary burning [2] the wall completely quenches the flame for a distance into the gas of approximately 0.1 to 1.0 centimeters from the wall depending upon the type of wall, its temperature, and other effects.

Flash-back occurs when the burning velocity somewhere exceeds the gas velocity. See Figure 4.[3] This condition is represented by curve 1.

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2. Guenther von Elbe and Morris Mentzer, "Further Studies of the Structure and Stability of Burner Flames", The Journal of Chemical Physics, Vol. 13, pp.89-100, 1945.

3. Bernard Lewis and Guenther von Elbe, "Stability and Structure of Burner Flames", The Journal of Chemical Physics, Vol. 11, pp. 75-97, 1943.

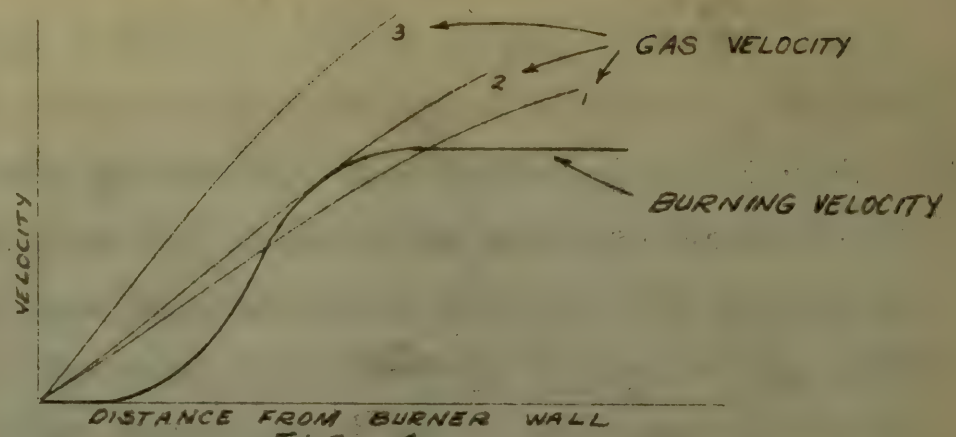

FIG. 4

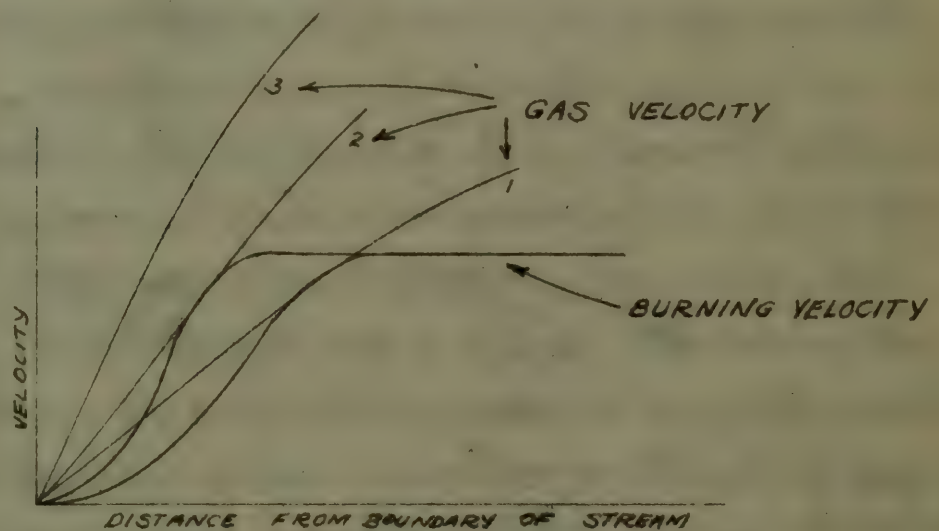

FIG. 5

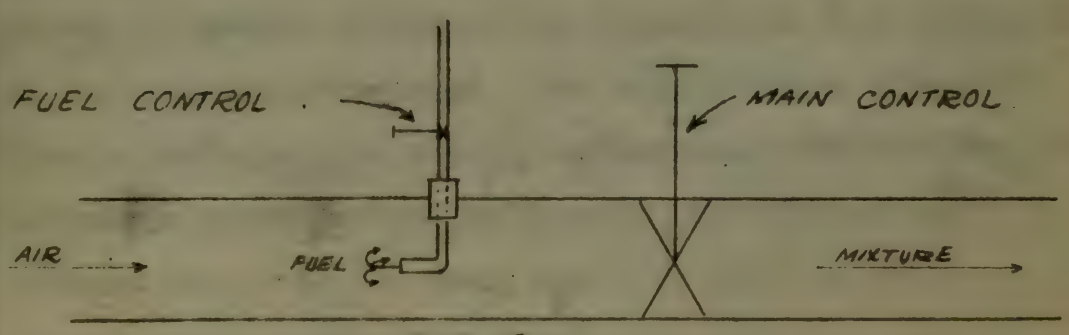

FIG. 6

As the flow is increased a critical velocity is reached, curve 2, where the gas velocity is barely equaled by the burning velocity and flash-back is just possible. With further increase in flow the velocity gradient is such that the gas velocity everywhere exceeds the burning velocity, curve 3, and the flame is swept out of the tube into the open air. The factors that determine the critical velocity gradient for flash-back are those that affect the burning velocity near the wall, namely the condition of the wall and the mixture composition.

Once outside the tube the combustible gases near the boundary regain their inflammability and the flame establishes itself as near to the rim of the burner as quenching allows. At some point, the gas velocity and burning velocities are equal, and the flame position becomes stabilized (Fig. 5 curve 1). With increased flow the combustion zone moves farther away from the rim gaining in burning velocity due to the increased distance from the wall and another point of stability is reached as in curve 2 Figure 5. However, the burning velocity vanishes toward the boundary of the stream as a result of dilution of the combustible mixture by the atmosphere and eventually a rate of flow will be reached such that the gas velocity everywhere exceeds the burning velocity and the flame will be blown off the end of the burner and extinguished. This point is termed "blow-off." There is thus a critical velocity gradient at the wall for flash-back and another higher gradient for blow-off. Between these critical gradients lies a range of stable operation, where increasing the flow mainly causes a further inclination of the flame surface from the normal to the gas stream.

These critical velocity gradients were calculated from the equations of velocity distribution in laminar flow by Lewis and von Elbe;[4] and their experiments showed them to be constant over a wide variety of tube sizes and gas velocities for a given mixture composition.

Analysis of the Problem. The salient principle to be taken from the foregoing description of the mechanism of combustion in the Bunsen burner is that the controlling factor for flame stabilization is the gradient of gas velocity between the ignited portion of the gas and that portion remaining to be ignited. For the flame holder this means the gradient of velocity between the turbulent low velocity region in the wake of the obstruction and the adjacent free flowing main stream. From aerodynamic considerations one concludes that the gradient of velocity between the turbulent wake region and the free stream should not be a function primarily of the shape of the downstream surface of the flame holder but more directly of the upstream shape, its surface condition, and the type of flow in the incoming stream. This implies that the shape of the downstream surface is of secondary importance only, an implication not in accord with the general practice which apparently calls only for variations in the type of concavity on the downstream surfaces with little regard for the shape of the upstream surfaces.

It was therefore planned that the first step in this investigation would be to measure the effect of the downstream surface upon

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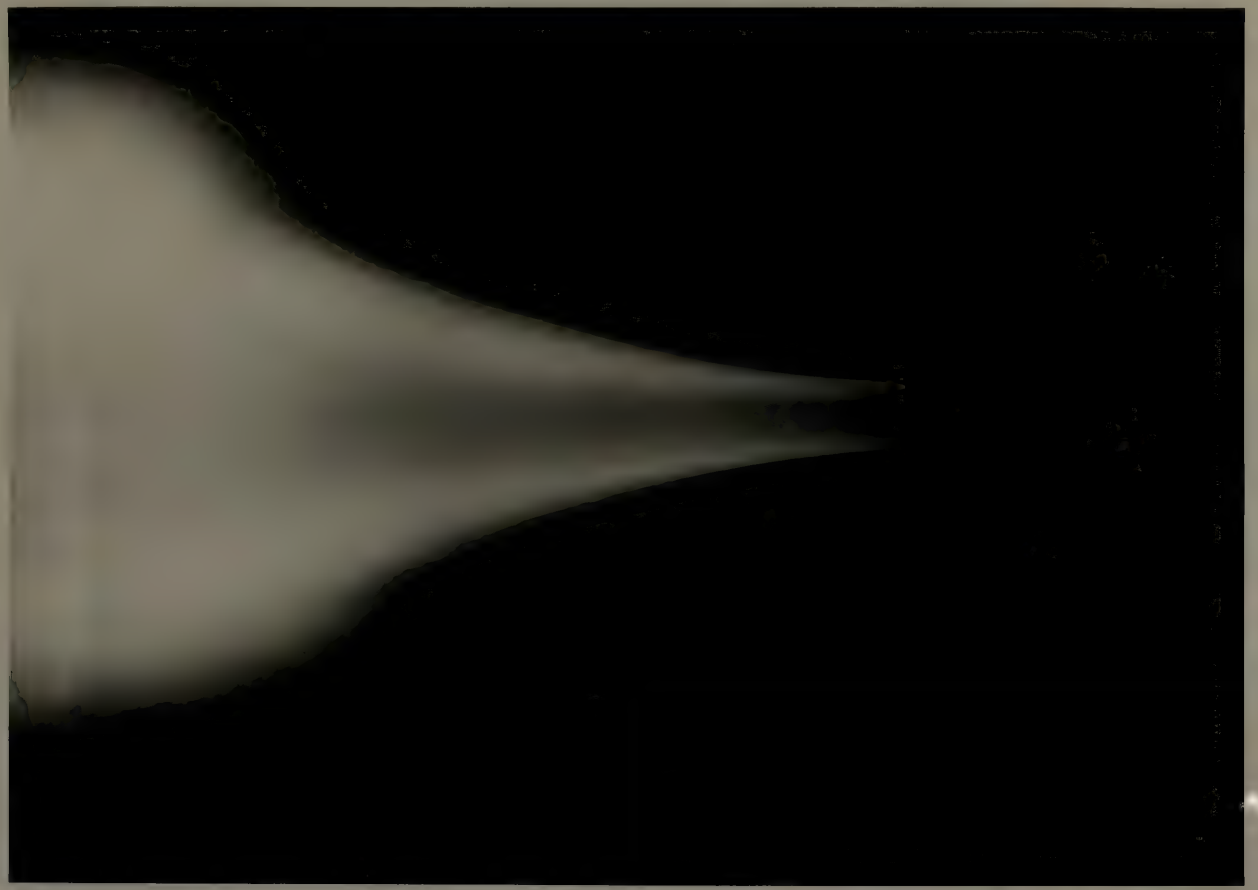
4. Guenther von Elbe and Morris Mentser, op. cit.

the flame holding ability of an obstruction in the stream, holding all other variables constant. This was done by constructing flame holders of long slender rods with differently shaped downstream ends so that the flow would then be identical for all flame holders except as affected by the shape of the downstream end. The rod was mounted coaxially in a pipe from which a combustible mixture of propane and air was blown. Ignition was accomplished by applying a torch to the turbulent wake eddy and the result was a flame in the shape of an inverted cone as in Photograph 1. Observations were made also upon the flow pattern, pressure effects in the stream, temperature distribution, and generally of all facts suspected of having a bearing upon the mechanism of flame holding. Based upon these observations a new type of flame holder was designed, built, and tested.



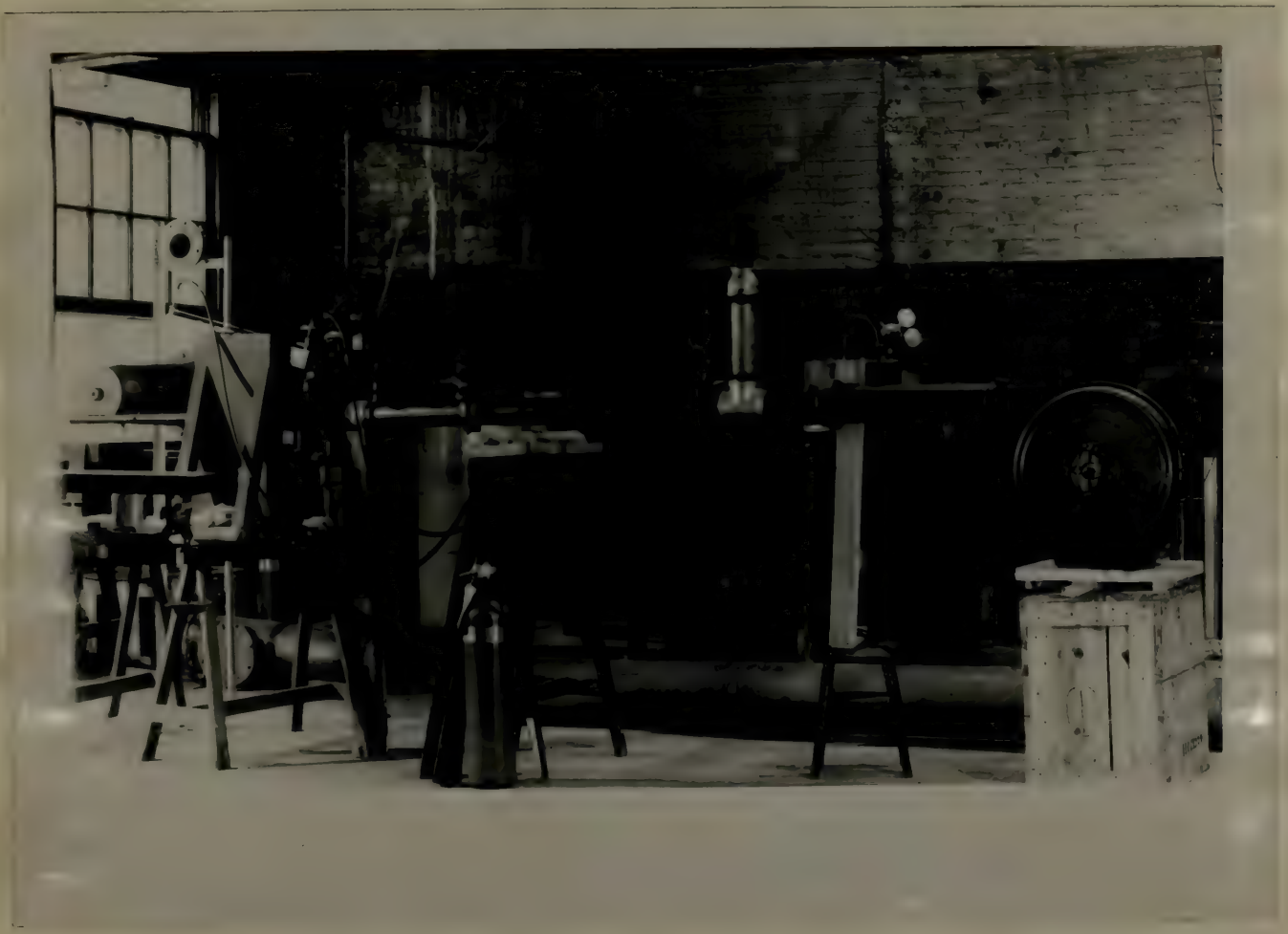
Photograph 1

THE EXPERIMENT

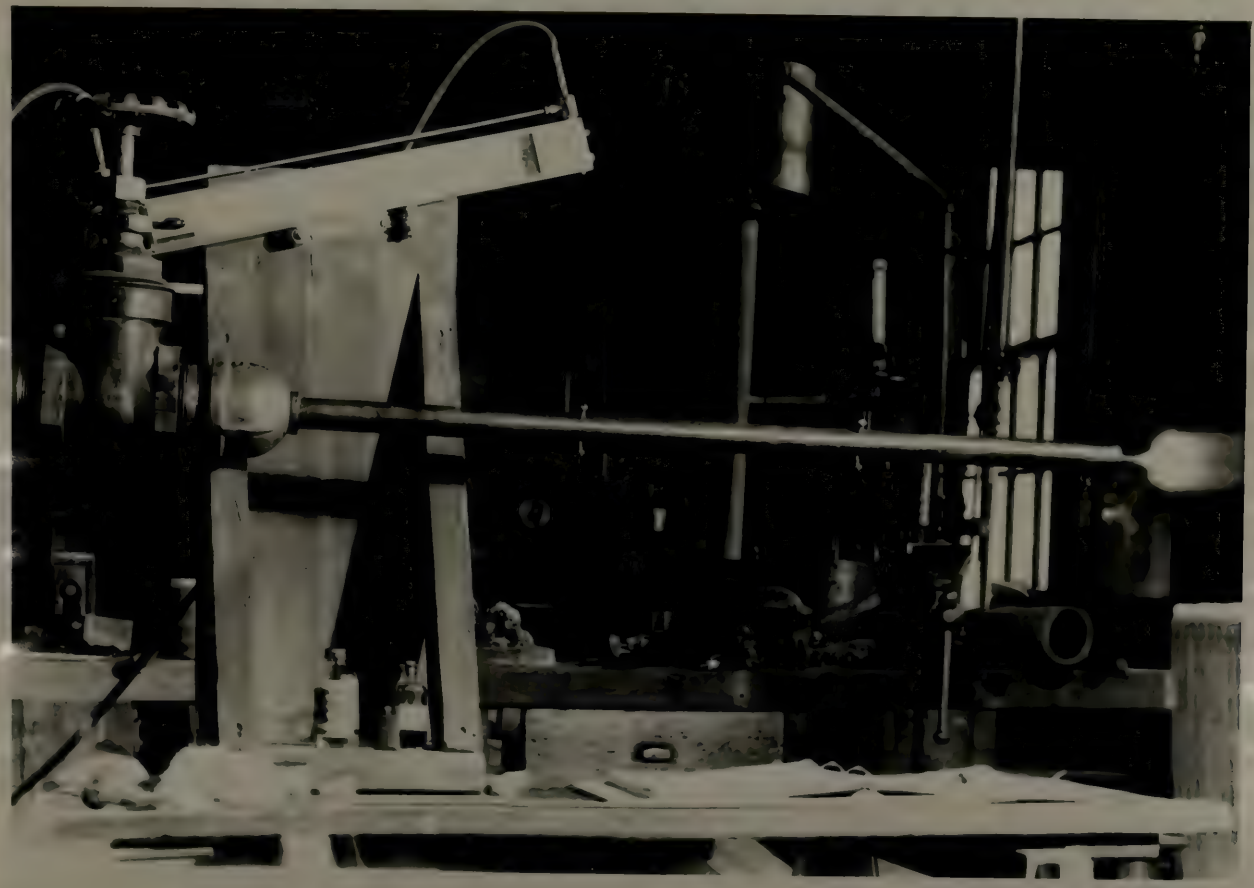
Since the object of making the experiment was to determine the effect of the downstream surface of a flame holder upon its ability to hold a flame, the apparatus was designed as simply as possible to fulfil that primary requirement. The experimental apparatus is shown in Photograph 2. Its essential parts are a blower for supplying air, a tank of liquid propane for supplying gaseous fuel by evaporation, metering devices for measuring the rate of flow of air and fuel, a control valve for the air system and another for the fuel system, three flame holders consisting of three long round slender steel rods having three different shapes on the downstream surfaces.

A detailed description of the parts follows. The relation of each part to the assembled apparatus is best seen by reference to Photograph 2.

Air Blower. The air blower was a centrifugal machine designed to supply air to metallurgical furnaces. Its rated capacity was one hundred seventy-five cubic feet of air per minute measured at atmospheric conditions; but, since the motor driving this blower was not as powerful as the one intended to be used, the actual output of the blower was far below the rating. It was sufficient for the purposes of this experiment, however. The blower was operated at thirty four hundred seventy five revolutions per minute and it ran quietly and with little vibration, delivering a supply of air at an almost constant back pressure of approximately twenty six inches of water gage. The total variation of



Photograph 2



Photograph 3

back pressure was not more than four tenths of an inch of water throughout the whole investigation regardless of temperature, rate of flow, or any other variables; and this was a very important factor in simplifying the measurement of air and gas flow as will be seen in the coming discussion. Since the designed flow of air was not taken from the blower it was sometimes found at low rates of flow to be in a state of pulsation, but the pulsations were very small in amplitude and fairly rapid so that no indication was seen on any of the manometers; and, more important, no effect of this pulsation could be seen in the flame although every effort was made to detect some change in burning characteristics when pulsation set in. It is believed that the effect of the metering orifice and the large control valve which was partially closed at all times completely eliminated the effect of pulsation before it reached the flame zone.

Air Metering. Air metering was accomplished by the use of a flat orifice plate built and installed according to the specifications of the American Society of Mechanical Engineers.[5] This measurement is based upon the measurement of the static pressure drop in a stream of fluid as it converges to pass through a restricted opening. The details of theory, design, and installation have been worked out very carefully by

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5. American Society of Mechanical Engineers,
Fluid Meters
Part 1 Theory and Application
Part 2 Description
Part 3 Their Installation and Selection
N. Y. Soc. 1931.

a committee of the A. S. M. E. and published in a special report, so those details are not presented here. The orifice was installed in a three inch brass pipe; and the orifice diameter was 1.531 inches. Pressure taps were installed about one half inch from the orifice plate, as specified for "flange taps". Pressures were measured with an inclined manometer which could be read accurately to a hundredth of an inch of water. Variations of temperature and pressure observed in the air system during all types of operation were not great enough to make significant changes in the indications of the metering system, and therefore the gas was considered to be atmospheric air in the calculations. The metering system as installed and used should give measurements of weight flow accurate to less than three percent.

Control Valve. The control valve was a three inch gate valve installed twenty-five inches downstream from the metering orifice plate and nine inches downstream from the point of fuel injection. In spite of its large size this valve was a very sensitive control device enabling the operator to control the flow within less than 0.005 inches of water-head on the differential manometer. In addition to controlling the rate of flow of combustion mixture, this valve performed the essential function of thoroughly mixing the fuel and air in the turbulent region created downstream from the valve. No difficulty was encountered as a result of bad mixing.

Fuel Supply. The fuel used was propane gas, C_3H_8, sold under the trade name of "Pyrofax" and, supplied in liquid form in tanks. This fuel has a vapor pressure of approximately 120 lbs./sq.in. at room temperature and therefore furnished a convenient fuel supply when obtained commercially in the form generally sold for rural home cooking and heating. Some of the pertinent characteristics[6] of propane as a fuel are tabulated below.

BTU per pound	21,500
Sp. Gr. (air = 1.0)	1.56
B. P.	-44° F
Critical Pressure	66.1 lb./sq.in.
Ratio of Specific Heats	1.153
Vapor Pressure at 22° C	132 lb./sq.in.

A pressure reducing valve of the type generally used on acetylene tanks in welding operations was installed in the fuel line to control the fuel pressure, and it maintained the pressure nearly constant but with slight fluctuations. These fluctuations are believed to have caused similar variations of small amplitude in the flame size and intensity. Since readings at blow-off could be repeated many times with almost identical results, it is believed that these very small fluctuations had no serious effect on the accuracy. A small copper pipe led from the fuel tank to the main air line and the fuel was injected against the air flow by a bent pipe inside the air line as shown in Figure 6. The fuel system as a whole constituted a metering device which was very reliable once

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6. Data furnished by the supplier.

it had been correctly calibrated, but the calibration was one of the most difficult parts of the measurement. It was carried out as follows.

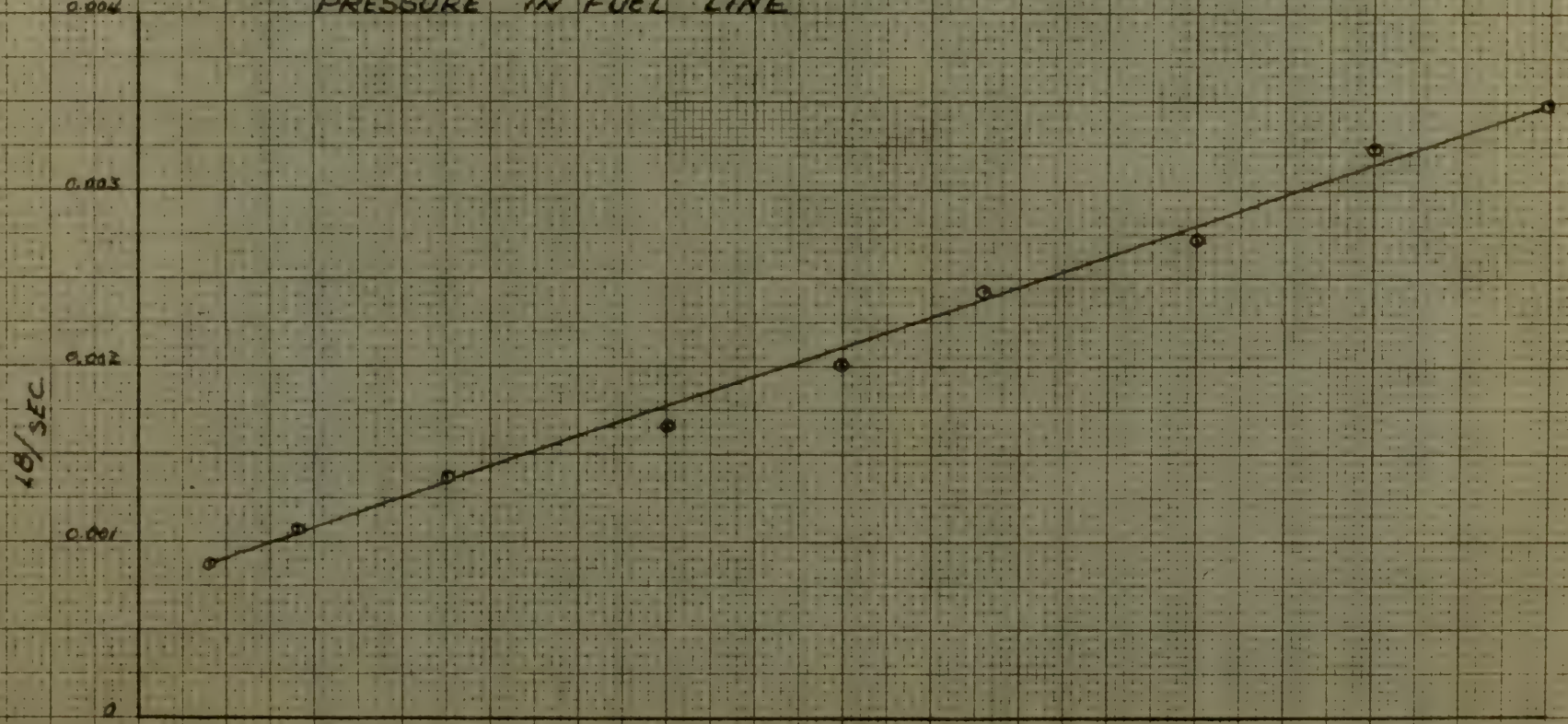
To the handle of the fuel control valve was welded a pointer which made contact with a positive stop device installed on the body of the valve in such a way that this control valve could be opened to exactly the same place repeatedly. The time was then measured for one pound of fuel to flow out through the system for a series of specified pressures in the fuel line. This data is tabulated in appendix A. Since the pressure in the air system to which this fuel discharged remained constant by virtue of the blower characteristics and the fact that the stream velocity was so low that the impact pressure had no significant effect, the pressure in the fuel line was the only controlling effect, provided the temperature of the fuel in the tank did not drop too far. It was found that with long continued burning evaporation cooling caused the temperature to fall so low that the density and viscosity of the gas were changed; this allowed a greater weight of fuel to flow per unit time than with normal room temperature gas even though the pressures in the fuel line were the same. Finally, however it was determined that the variation from normal was not important if the vapor pressure in the tank were kept between 120 and 105 lb./sq.in., the vapor pressure being a measure of the temperature. By observing this precaution very accurate measurements could be made as will be seen from the tabulated times in appendix A, and from these measurements the fuel calibration curve, Curve I, was made up.

CURVE 1

POUNDS PER SECOND FUEL FLOW

VERSUS

PRESSURE IN FUEL LINE



Thereafter with the use of this curve, knowing the pressure in the fuel line, one could pick off accurately the weight rate of flow of fuel, keeping in mind all the time that the vapor pressure in the tank must be maintained between 105 and 120 lb./sq.in. Due to the difficulty encountered in the fuel calibration and the fact that the calibration curve finally obtained was almost a straight line contrary to expectation, this calibration was checked and rechecked several times during the course of the investigation, and was repeatedly verified. Consequently it is believed that by its use very accurate measurements of the fuel weight rate were obtained. It will be seen that great accuracy in this measurement is essential to the correct measurement of the blow-off velocities.

Flame Holders. The flame holders were constructed of steel rods of diameter = 0.2475 inches and length = thirty six inches. These flame holders were mounted coaxially in a one-inch pipe three feet long installed eight inches downstream from the large control valve. They were held in place by set screws located one foot and two feet from the downstream end. These set screws together with the control valve insured a high degree of turbulence in the air stream. For all the recorded runs, the ends of the flame holders protruded one-half inch from the end of the one-inch pipe, but it was observed that no measurable change in performance occurred when the end of the rod was moved from the plane of the end of the pipe to a plane one inch downstream from the pipe.

Temperature and Pressure Measurements. A sliding rack device to which was attached a chromel-alumel thermocouple was used for a temperature probe of the combustion region. See appendix A for tabulation. Two scales were attached to the rack: the "x" scale which measured to one sixteenth of an inch was used to measure the distance downstream from the end of the flame holder; and the "y" scale which measured thou-andths of feet was used to measure distances perpendicular to the flow. It was very difficult to maintain a stable flame at temperatures low enough for the use of a thermocouple and this factor severely limited th, amount of information that could be obtained by this method. The results obtained are questionable because of (1) the long exposure of the thermo-couple and its fittings to temperatures near the thermocouple's maximum limiting temperature, and (2) the probability that the presence of the thermocouple altered the structure of the flame, (3) radiation errors. However, in spite of probable inaccuracies some very interesting infor-mation about the temperature distribution in the flame cone was obtained and is shown in Curve II. A pressure probe was made using an impact tube installed in the same sliding rack, with doubtful results. Severe temperatures also limited the accuracy of these measurements. Temperature and pressure measurements were made in conjunction with Lieut. Comdr. Oliver D. Compton, U.S.N. who prepared Curve III from raw data obtained jointly.

Schlieren. Schlieren photographs were made by Capt. Russell Harrington, U.S.A. for the purpose of showing the flow around the downstream ends of the flame

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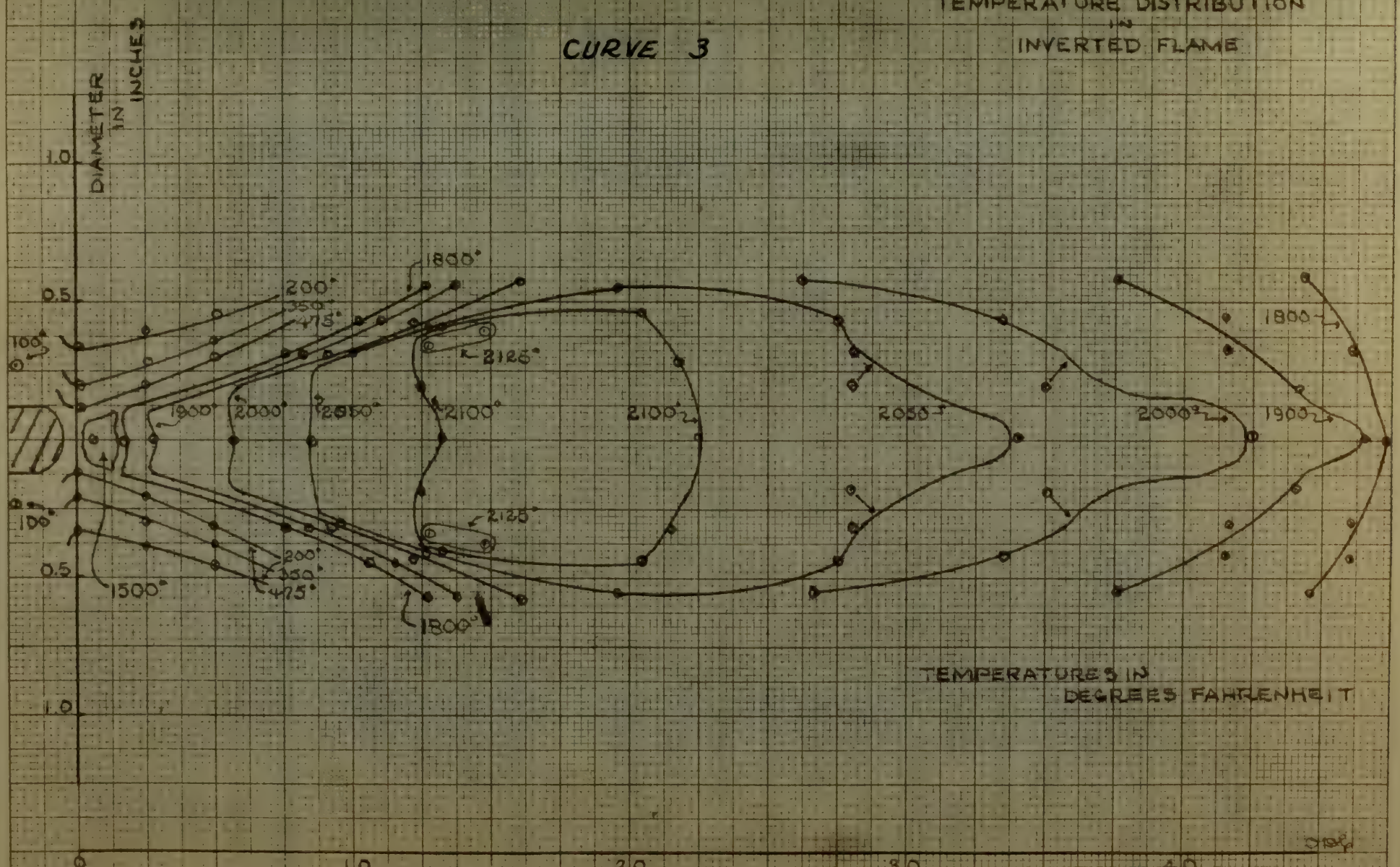
CURVE 3

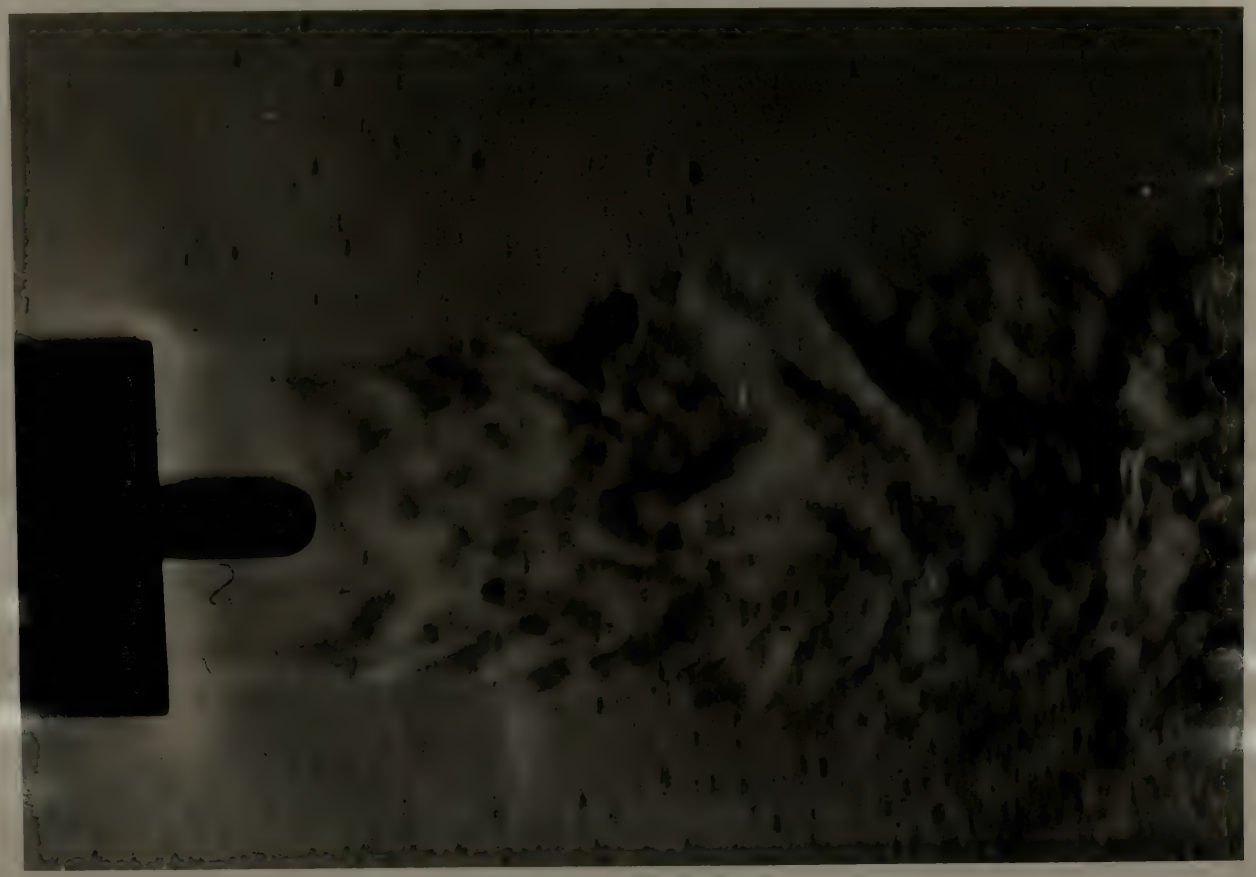
TEMPERATURE DISTRIBUTION IN INVERTED FLAME



TEMPERATURES IN DEGREES FAHRENHEIT

holders. The velocity of air available was not sufficient to make the requisite density changes, however, and that flow was not revealed. Two interesting schlieren photographs are presented that do show something about the flow of the stream as a whole. Photograph 12 shows the shape and divergence of the emerging stream without burning. It was made by heating the air in the one-inch pipe with a gasoline torch which caused sufficient density change to register on the schlieren apparatus. Photograph 13 shows the flame cone very clearly. Note the extreme turbulence, the divergence ahead of the flame, the distance between the flame holder and the flame. Background heat waves are those drifting past in the atmosphere from the heated one-inch pipe and have no bearing on the flame process. Both photographs were made at 1/30,000 second stopping the motion entirely and showing that the smooth cone observed by eye and photographed with ordinary shutter speeds are not at all a true picture of the burning process.

Observations of Blow-off. The main observations were those intended to measure the rate of flow at the instant of blow-off from each of the three flame holders over a range of mixture compositions. A study of the fuel characteristics was not intended and the great importance of the composition of the burning mixture is solely due to the fact that the composition profoundly affects the burning characteristics. Therefore, the only sound basis of comparison of the three flame holders was comparison for the same mixture, and this could be accomplished with the experimental set-up in use only by making measurements over a range of mixtures. It should be held constantly in mind in evaluating the results of this



Photograph 12

Photograph 13

investigation that determination of the absolute performance of the three flame holders was not the primary object, but determination of relative performance among the three was the goal. Due to this fact, system errors applying equally to each of the three surfaces would not affect the conclusions drawn. This is not to be taken as an implication that any of the measurements are inaccurate except as noted or that any were carelessly done.

Ignition was accomplished by blowing a fairly rich mixture past the flame holder at a low velocity and holding a flaming wad of waste near the turbulent region immediately downstream from the flame holder. After ignition the flow could be increased and the mixture could be changed at will within the mixture limits of inflammability and the flow limits of stability. The appearance of normal mixture burning, one neither "rich" or "lean", from the flat ended rod is seen in Photograph 1. The pipe and flame holder are visible at the left edge of the picture, which is slightly larger than life-size. Note that the flame does not make contact with the metal but it becomes luminous at a distance of approximately 0.1 inches away from it apparently as a result of the quenching effect of the metal. However, the luminous region is not necessarily the most reactive region, since a large percentage of the reaction may occur ahead of the luminous region.[7] The average velocity of the stream in this picture is about thirty-seven feet per second, and at this velocity the flame front is very nearly parallel

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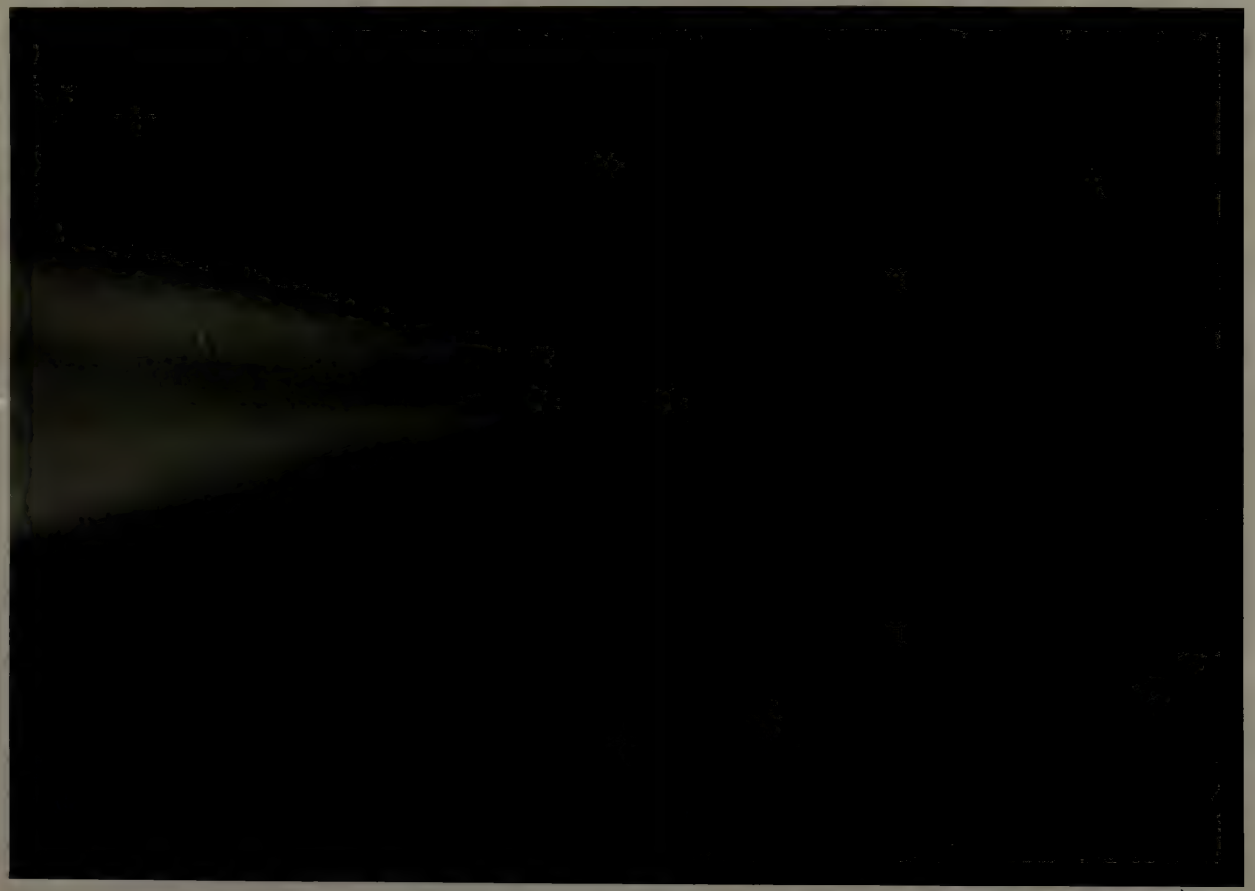
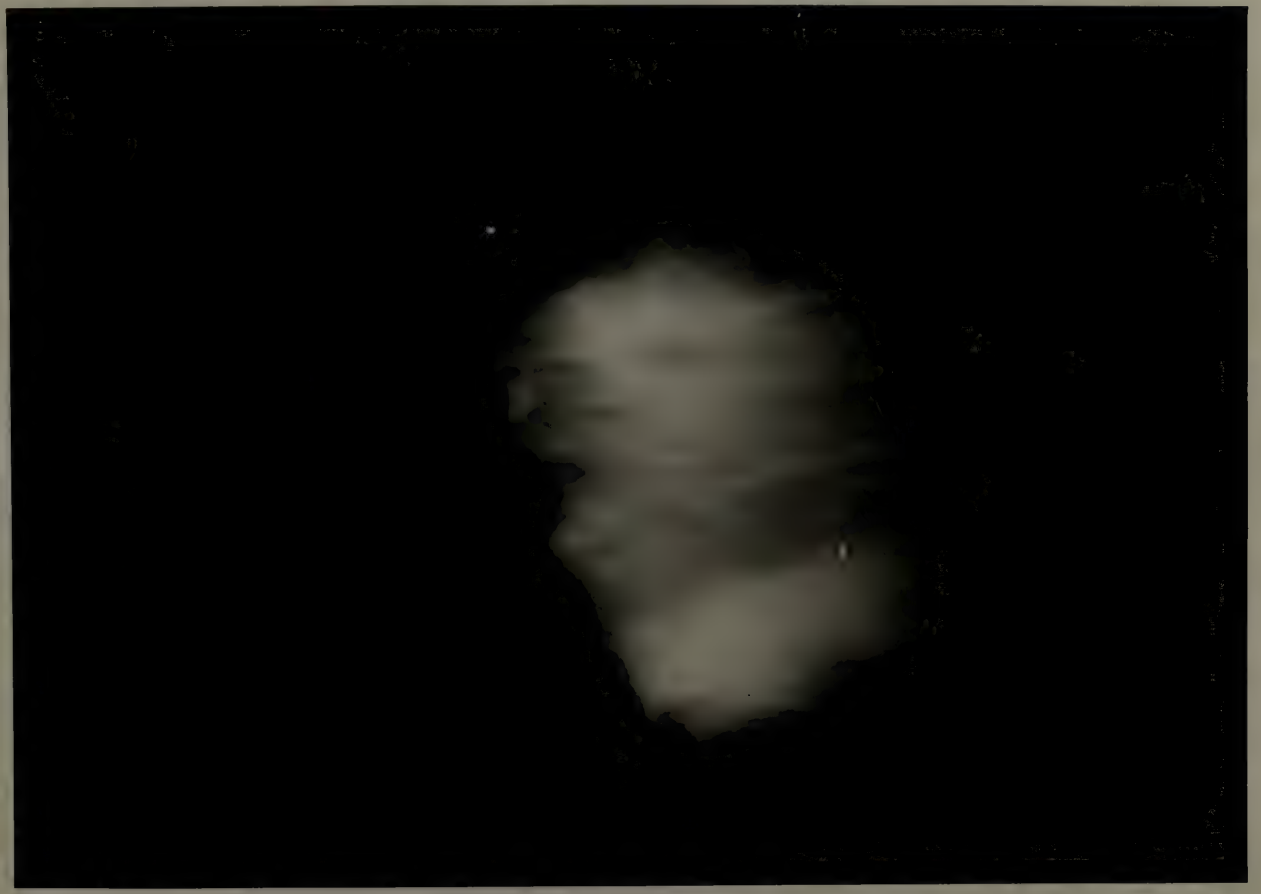
7. As described by Dr. Herad of the General Electric Company before the jet propulsion students at Rensselaer Polytechnic Institute in March 1947.

to the flow for a distance of two or three flame holder diameters downstream from the flame holder, at which point it begins to diverge in a curvature that increases with distance downstream. The fuzzy abnormal lumps on the cone surface near the base of the cone are due to a doughnut shaped turbulent region created by the outside atmosphere making eddies around the rapidly flowing main stream. This phenomenon can be seen better in Photograph 11 taken at a much lower rate of flow so that this turbulent annular vortex has moved closer to the pipe entirely obscuring most of the divergent section of the cone which still exists inside the doughnut. When flow is decreased sufficiently this vortex moves back until it makes contact with the edge of the pipe and forms a Bunsen burner type of flame, sometimes with the divergent cone from the flame holder still in place and burning well. However, this roll of turbulent outside air is a function of the pipe edge and the ambient atmosphere rather than of the flame holder and no particular study has been given to it. It is worthy of note, however, that the maximum flame temperature appears to be located within the cone adjacent to this vortex.

Photograph 5 shows a flame like that of Photograph 1 in every respect except that the mixture is lean. Although the velocity is still the same, the luminous flame does not approach the metal closer than about three tenths of an inch, and the flame front at first converges instead of remaining parallel. The shape of the turbulent region just downstream of the flame holder is clearly visible due to the low intensity of the flame surrounding it. The angle of divergence in the lower part



Photograph 5



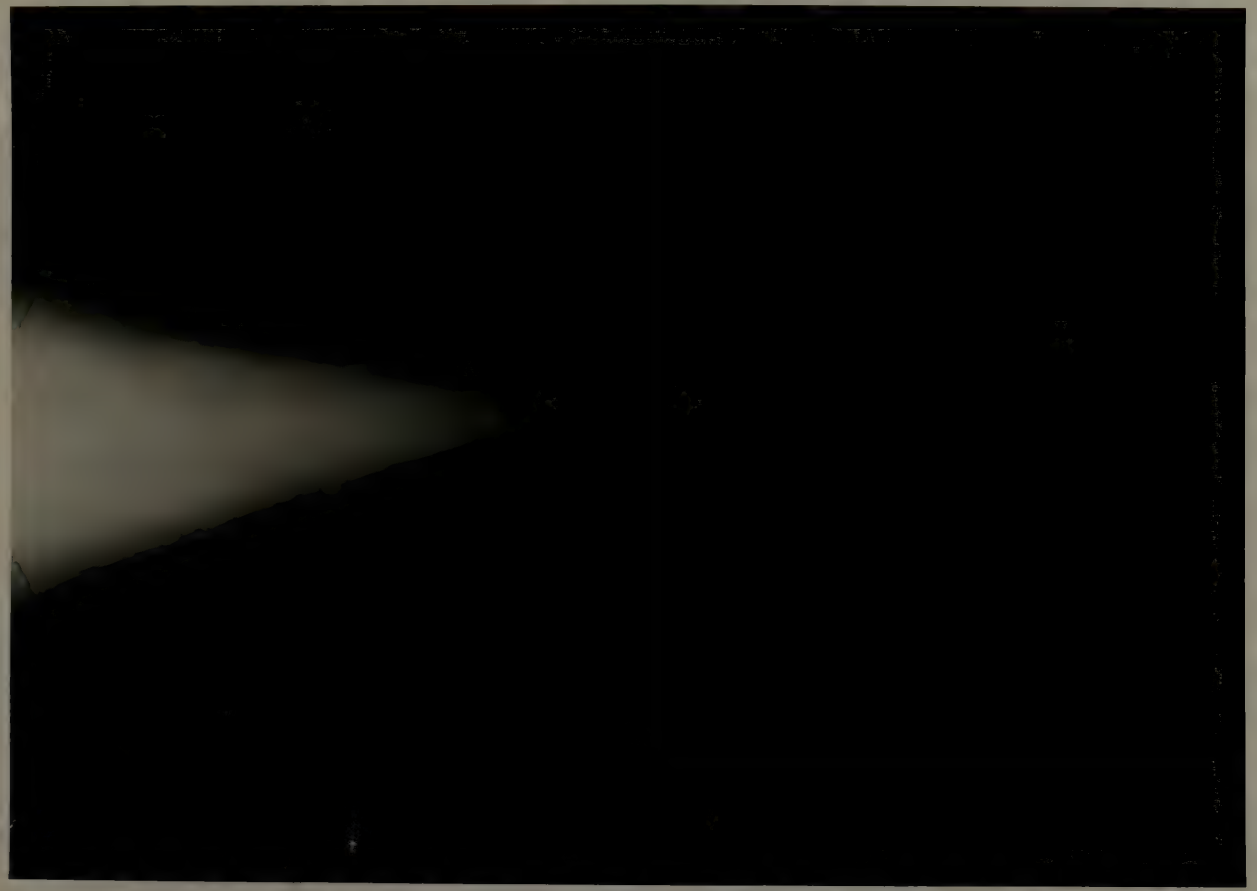
Photograph 11

of the cone is much smaller for the lean mixture than for the normal, and in general the luminosity is not so great. Temperature measurements show the temperature to be far lower also.

Photograph 6 is similar to Photographs 1 and 5 except that it is a rich mixture burning at the same velocity. Note the sharply outlined turbulent region, the very narrow neck in the flame, and the low luminosity. Once intense burning was started, as it was in the vortex at the right of the picture, luminosity and temperature were high. It is possible at times to cause this flame to neck down until it separates entirely with a dark space between the burning at the tip of the flame holder and the burning at the base of the cone, but this is an unstable situation that can be maintained only for a moment. It is probable that when flame separation occurred the intervening dark region was nevertheless a region of high chemical reactivity; introduction of any measuring device such as a thermocouple served only to disrupt the flow pattern and cause blow-off or return of the luminous flame.

Photograph 7 shows the type of flame obtained with a normal mixture at higher velocities, this one being at approximately sixty-five feet per second. Although the end of the flame holder cannot be seen in the picture its position can be accurately judged from the foregoing photographs. Photograph 8 shows the cone from the round ended flame holder at very low velocity, approximately three feet per second. In this picture the angle of the cone can clearly be seen to be larger than before. Note the slight curvature at the upstream edge of the flame;

Photograph 6



Photograph 7

Photograph 8

this is believed to be a result of the outward radial flow from a tiny vortex in the wake of the flame holder. The flame from the flat or concave surface is essentially the same in appearance as this flame from the round ended rod.

One phenomenon not apparent from the photographs but readily visible to the eye is the variation of color with mixture. The flame is light blue for a lean mixture becoming more luminous but remaining blue as more fuel is added to the mixture. When sufficient fuel is added to cause the necking down shown in Photograph 6, the color changes to green in that narrow region and regains the normal blue color in the more luminous region downstream. This green color is believed to be due to the presence of excited formaldehyde in the flame, a manifestation of the so-called "cool flame" reported in the literature of chemical kinetics.[5]

The rates of flow at blow-off were measured by setting a given weight flow of fuel as previously described in the calibration discussion and increasing the flow of air until the flame blew off the end of the flame holder. The reading of the inclined manometer at that instant gave the rate of air flow and this could be combined with the rate of fuel flow to give the total rate, the mixture composition, and together with the area of the annular opening, an average velocity. Volume rates

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5. Von Elbe and Lewis, Journal of Chemical Physics, Vol. 10, p.366, 1942. and H. B. Burk and Oliver Grummit, The Chemical Background For Engine Research. Interscience Publishers, Inc. New York, N.Y., 1943.

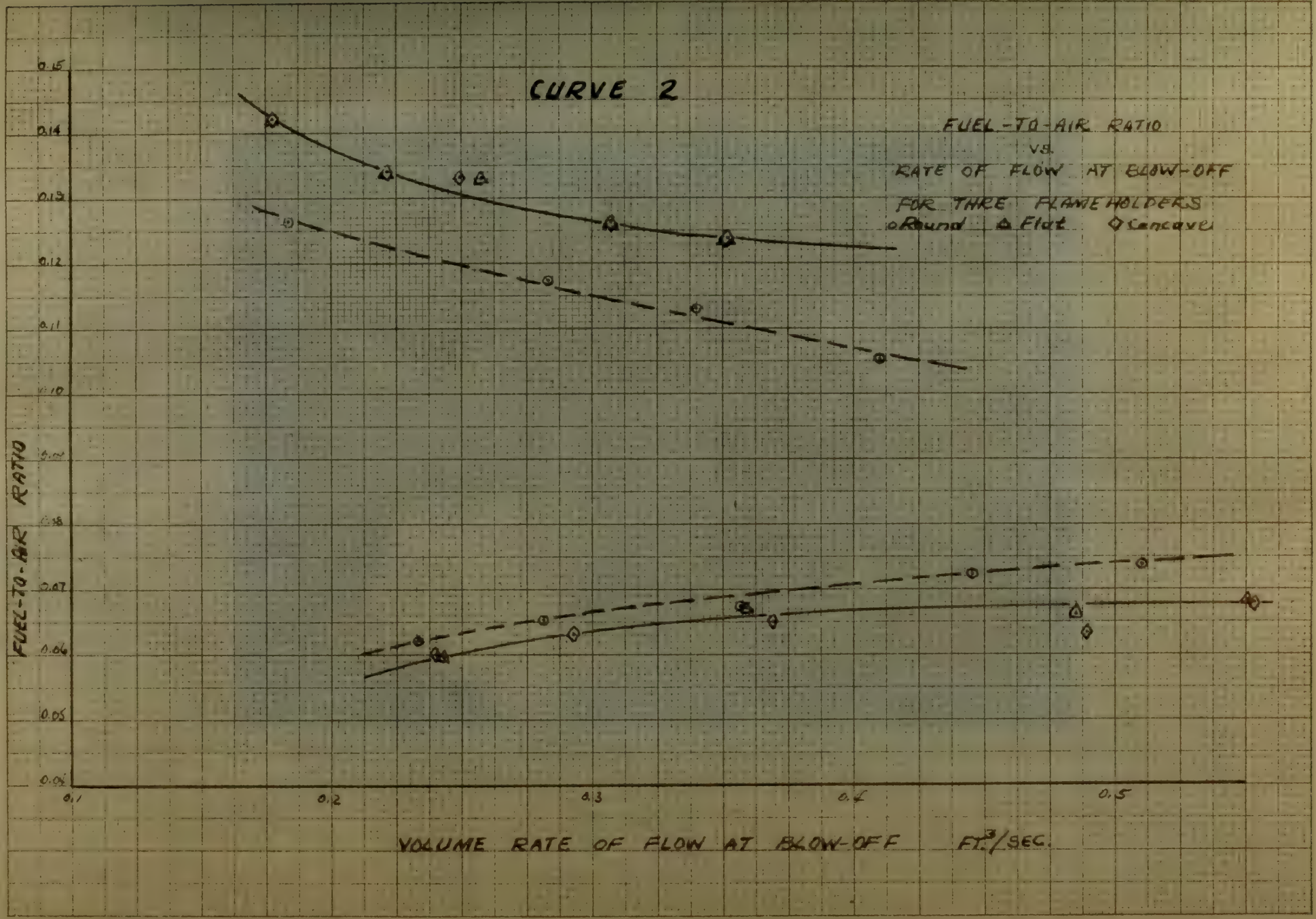
of flow were used in the report instead of velocities in order to avoid the complications arising out of the velocity profile; since volume rates were exactly proportional to average velocities, the size of the exit opening remaining constant, this parameter was a measure of performance equally as good as velocity would have been.

It was possible to get very consistent readings once the fuel calibration problem had been solved and the technique of controlling the flame had been acquired by practice. The raw experimental data is listed in appendix A and examination of the deviations in the readings will give some idea of the reproducibility possible. However the range in which this reproducibility was obtained was strictly limited, and no readings were reported outside of this range. At the upper flow the limit was caused by the fact that the flame instead of blowing off at a definite velocity would gradually decrease in intensity and size while raw fuel was blown through it and into the atmosphere without burning. If this process were allowed to go to completion the flame would diminish until only a very tiny tip hung onto the end of the flame holder extending about two diameters downstream therefrom. Furthermore, at rates above a certain definite value for each mixture marked instability of the flame set in causing the manometer to fluctuate wildly over a range of about six tenths of an inch. In order to avoid errors from these causes, the highest reported data was taken at a rate of flow approximately 75% of the rate at which it could first be observed that raw fuel

was escaping. There is no certain way of knowing that complete combustion took place under that condition but it is considered to be a conservative approximation. The lower limit was set by the action of the large turbulent vortex at the base of the cone which moved upstream until it made contact with the pipe rim and formed a Bunsen burner type flame. Between these limits very consistent results could be obtained. The raw data were converted as shown in appendix B into the form plotted in Curve II.

One or two other observations of the action of this flame should be noted. It was observed that at the instant when the flame blew off, the differential head across the metering orifice increased by approximately 0.1 to 0.3 inches of water depending upon the rate of flow. This indicated that the back pressure caused by the flame was sufficient to retard the flow by that amount. Additional evidence of the presence of back pressure from the flame is seen in the divergence of the stream prior to entering the flame while the normal divergence without burning is much smaller. Photographs 9 and 10 show this divergence very clearly by the path of the smoke particles introduced at the edge of the stream. Photograph 10 was taken at a rate of flow approximately half that of Photograph 9 and the effect is more marked in the slower stream.

Another observation that could not be photographed was the presence at times of a tiny vortex visible in the turbulent region immediately downstream from the flame holder in the apex of the dark region seen in Photograph 5. This vortex had the appearance of a ball of fire about a tenth of an inch in thickness and twice as long in a rapid flow as if the streamlines were passing around and through a doughnut, reversing direction twice.


CURVE 2
FUEL-TO-AIR RATIO
VS.
RATE OF FLOW AT BLOW-OFF
FOR THREE FLAMEHOLDERS
○ Round △ Flat ◇ Concave
FUEL-TO-AIR RATIO
0.15
0.14
0.13
0.12
0.11
0.10
0.08
0.07
0.06
0.05
0.04
0.1
0.2
0.3
0.4
0.5
VOLUME RATE OF FLOW AT BLOW-OFF FT.³/SEC.

Photograph 9

Photograph 10

INTERPRETATION

The most significant information obtained in this investigation can be read from Curve II, the plot of the mixture composition versus the rate of flow at blow-off. The flat surface is seen at once to have a performance identical with that of the concave surface, an observation remarkable in view of the practically universal use of a concave downstream surface in flame holders. Contrary to original expectation on the basis of equal velocity gradients from the three different rods, the performance of the round-ended rod was not as good as that of the other two. The divergence is greater than appears at first glance at the curves due to their flat slope. Thus for a given mixture in the lean range the rate of flow at blow-off from the flat and concave surfaces is thirty to fifty percent greater than for the rounded surface even though the curves lie very close together. The flat nature of these curves shows why it was essential to obtain accurate measurements of fuel flow, since a change of the fuel-to-air ratio from six hundredths to seven hundredths more than doubles the rate of flow at blow-off.

The identity of the curves for flat and concave surfaces well supports the theory that the significant characteristic of flow for stable burning is the velocity gradient in the stream; and it is believed that the performance of the rounded surface can also be explained on the basis of this theory.

At low rates of flow with the rounded surface it was observed that the flame did not originate from the outside radius of the rod but from a point on the curved surface such that the diameter of the tube of

flame near the surface was smaller than the full radius of the rod. See Photograph 11. Evidence from the pressure probe also supports this observation. Thus due to the location of the point of separation of flow the size of the flame holder was effectively reduced. See Figure 7. Since the velocity gradient is determined by the area over which friction forces act to retard the flow near the surface, a rod of smaller radius would produce a higher velocity gradient than one of larger radius with the same rate of flow, and therefore we would reasonably expect to get blow-off at a lower rate of flow with a smaller radius. This is in accord with observations.

If this were the only factor at work it could be expected that as the rate of flow increased and the point of separation moved out and around the curved surface toward the full radius that the performance of the round end should more nearly approach that for the flat and concave ends. This was not observed. It may be that the accuracy of the measurements and the limited range reported are not sufficient to show such a trend if it exists, but a plausible explanation can also be found in the study of velocity gradients around a sphere, since the shape of the rounded flame holder surface was approximately hemispherical. Figure 8 after Dodge and Thompson[9] shows how the velocity profile varies when a stream separates on such a surface. The point of separation is always a point of zero velocity gradient at the surface, but the size of the region of zero gradient is apparently too small to hold a flame for

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9. Dodge and Thompson, Fluid Mechanics, McGraw-Hill Book Company, Inc., New York and London, 1937.

FIG 7

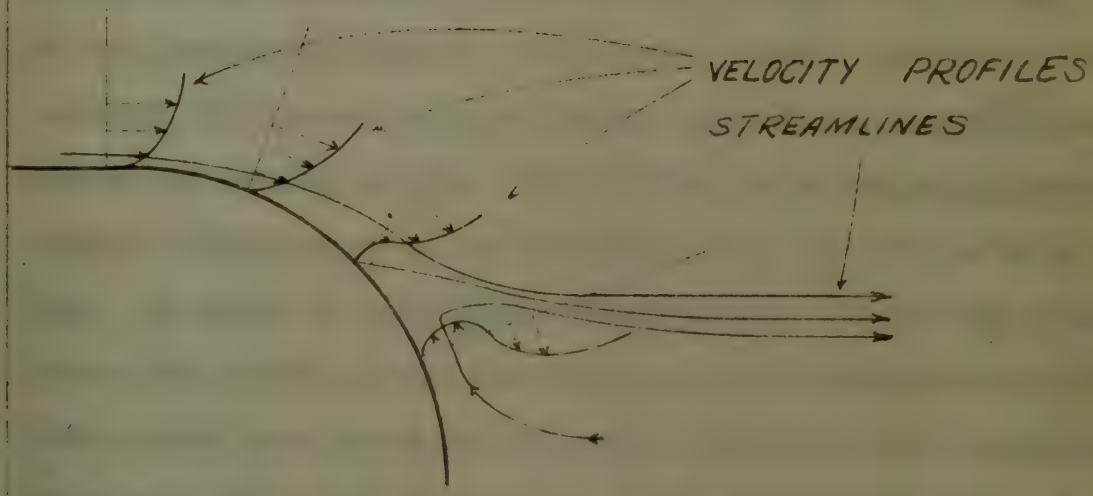

FIG 8

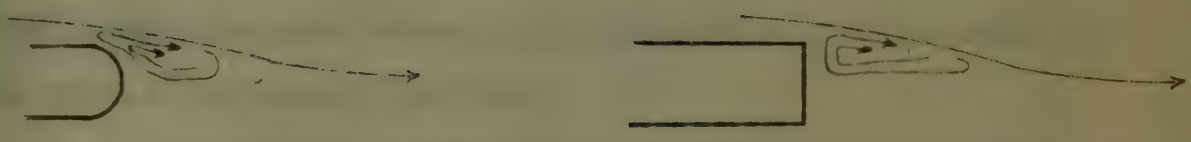

FIG 9

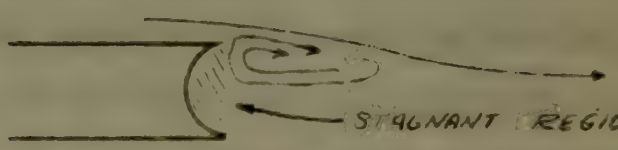

FIG 10

otherwise one could always burn wherever separation occurred. The velocity gradients surrounding such points must be too great at high rates of flow to allow retention of flame. Downstream from the point of separation there is a reverse flow close to the surface while further from the surface the flow goes downstream. An indication of the existence of such a back flow on the rounded surface is the curvature of the forward edge of the flame in Photograph 8. The velocity gradient near the envelope enclosing this reverse eddy must be much greater than it would have been without the reversal of flow. Thus another factor tending to produce a higher velocity gradient for the same rate of flow is seen to be at work. The effect of this reverse flow increases with the rate of flow because the reverse flow is directed more nearly upstream as the separation point moves toward the full radius and meanwhile the magnitudes of the velocities of the main stream and the back flow both increase; while the first cause, effective decrease in diameter of flame holder, decreases with increased rates of flow. How the two effects balance out cannot be surely said from these measurements but the indication is that in this flow range the rate of increase of one is about offset by the rate of decrease of the other.

The same type of back flow exists with the flat and concave surfaces as with the round one except that the back flow never can point upstream near the separation envelope as with the round surface and therefore the effect should be less severe. For the flat and the maximum angle at which the two flows could merge is ninety degrees. See Figure 9. Photographs indicate the existence of this flow by the same

curvature at the leading edge of the flame. Practically identical observations were made for the concave surface, which indicates that the back flow must not have been circulating back into the concavity and emerging practically parallel to the main stream as might be expected, but must have been taking some such course as shown in Figure 10 due to a pocket of more or less stagnant air in the concavity. This could explain why it behaved exactly as the flat ended rod.

The above close description of the back eddy flow cannot be said with certainty to have occurred as described but there is evidence from the photographs, pressure probe, and visual observations[12] that such flows did occur. On that basis it is reasonable to assume that with a larger concave flame holder and with higher velocities the eddy flow might circulate through the concavity and emerge almost parallel to the main flow with considerable velocity thus reducing the velocity gradient and resulting in a better flame holder than a flat end of the same size. However, this might produce a more severe velocity gradient within the eddy making the performance worse. This conjecture can be settled only by careful and detailed investigation of such a flow.

The velocity gradients at blow-off were not reported for the reason that they could not be determined. In the work of most workers in the Bunsen burner field only laminar flow was used and for that condition the gradient can be found as follows. The velocity distribution in the boundary layer of a flat plate for laminar flow is given by

$$u = U\frac{y}{\delta}\left(2 - \frac{y}{\delta}\right)$$

12. For further evidence from the water table about the flow in the back eddy, see Addendum No.1, p.35.

where u is the velocity at any point, U is the velocity in the free stream, y is the distance from the flat plate, δ is the total thickness of the boundary layer. For a pipe this U can be taken as the maximum velocity in the axis of the pipe since the whole flow is boundary layer, and δ corresponds to the radius of the pipe. Differentiating with respect to r, and taking the limit as r approaches R, the radius of the pipe, one obtains the gradient at the surface of the pipe:

$$\lim_{r \to R} \left(- \frac{du}{dr} \right) = \frac{4\,V}{\pi R^3}$$

where V is the volume rate with time. A similar operation will yield the value of the rate of change of velocity with r for an annular space.

However, in the case of a turbulent boundary layer the expression for the distribution of velocity with distance is

$$u = \bar{u} \left(\frac{y}{\delta} \right)^{\frac{1}{7}}$$

which differentiates to zero at the limit. According to this relation the rate of change of velocity with distance from the wall is zero at the wall, a meaningless statement for this practical problem. Either the above relation for velocity and distance does not apply near the wall, or the point at which the gradient is significant for purposes of this investigation is at some small unknown distance removed from the wall. Although the actual velocity gradient cannot be determined for this experiment it can be safely said that for a given rate of flow in the apparatus used the velocity gradient will be the same for all three

flame holders except as noted for the rounded surface; and, to repeat, it is the comparative performance that is sought, not the absolute performance.

The temperature measurements presented in Curve III are suspected of inaccuracies due to intense heat on thermocouple fittings, long exposure to high temperature, radiation errors, and the probability that the presence of the thermocouple alters structure of the flame zone. However, the isotherms are undoubtedly approximately correct and show definitely that practically all the temperature rise occurs in a very narrow zone located approximately where the luminous flame cone is located. There is undoubtedly some temperature rise ahead of this zone but the amount of rise or its extent in space is not reliably shown in Curve III. The low temperature region immediately downstream from the flame holder is probably the preheated mixture that has passed through the flame zone without burning and will later emerge and burn near the envelope where the turbulent region meets the free stream. No good explanation is given for the annular region of highest temperature near the base of the cone.

The pressure probe of the flame region gave unreliable results due to the fact that the equipment could not withstand the high temperature and that it disturbed the structure of the flame. Also the meaning of impact pressure is not clear since there is uncertainty regarding the static pressure distribution in the reaction zone. The only reasonably clear fact emerging from the pressure probe is that in general the total pressure is somewhat less downstream from the flame cone than

upstream. Isobars appear to run parallel to the flame front.

This is in accord with the previous observations that a back pressure was created by the combustion reaction that retarded the flow and caused divergence of the stream. The cause[10] of the back pressure is believed to be due to the reaction force from the expanding and accelerating gas as it passes through the high temperature gradient in the flame cone, the component of this force parallel to the flow producing retardation and the normal component producing divergence. The question arises whether the pressure drop across a flame zone so often referred to as the "loss of pressure due to burning" by combustion investigators in the jet field is a real loss or only an apparent loss due to the back pressure created by burning.

The fact that the flame originates some distance from the steel flame holder rather than at its surface is interpreted to be an indication of quenching by adsorption of the active species and by cooling. This action is believed to have much significance in the flame holder process. It will surely limit the size to which flame holders can be reduced for when the total turbulent region is within the distance of total quenching no flame can possibly be retained. Furthermore it appears from the observations that the quenching distance increases with increased flow. The exact explanation of this is not at present understood and a full

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10. H. F. Fiock, "Combustion Research", Chemical Background for Engine Research, Ed. by Burk and Grummit, Interscience Publishers, Inc., New York.

and G. von Elbe and M. Mentser, "Further Studies of the Structure of Burner Flames," The Journal of Chemical Physics, Vol. 13, 1945.

description of the burning process cannot be made without that understanding. It should be observed that with rates of flow so low that the end of the flame holder became hot the flame gone after a long time burning would back up over the edge of the flame holder and hang on to the hot cylindrical surface. After thus heating the rod further it would continue to creep upstream being anchored by the hot surface of the rod rather than by the turbulent region. This shows how temperature affects the quenching action and how important quenching is to the action of the flame.

In view of its importance a brief description of the chemical kinetics of the quenching action is given. Hydrocarbon and oxygen molecules do not react directly in the combustion process but go through a series of steps involving free radicals. A typical branching chain series leading to explosion is given.[11] Note the initiation by a free radical.

$$H + O_2 = OH + O$$

The products of this reaction then react as follows

$$OH + H_2 = H_2O + H$$

$$O + H_2 = OH + H$$

This O H then reacts with hydrogen

$$OH + H_2 = H_2O + H$$

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11. von Elbe and Lewis, The Journal of Chemical Physics, Vol.10, p.366, 1942.

After this series of steps not only the original hydrocarbon atom remains but also two more hydrocarbons in addition to it, all capable of initiating a new chain which in turn branches again. If this process were to continue unchecked the mixture would explode in a matter of microseconds. All the branches and the original chain can be suppressed by sufficiently rapid chain breaking processes. One of the many ways in which this may be done is by the presence of a third body, either an inert molecule, a wall, or any good acceptor of energy. In the presence of a third body, M, the following reaction may occur

$$H + O_2 + M = HO_2 + M$$

The third body acts in this reaction to accept the bond energy released with the union of H and O_2 for unless that energy can be dissipated the HO_2 particle flies apart after a brief interval. When the last reaction occurs the chain is broken by the removal of the chain carrier, H. This is one way in which a wall can inhibit a reaction. Another way is by adsorption of the active species to the wall where they react with other radicals and become neutral thus breaking more chains.

The nature of the surface affects the quenching properties profoundly, a fact that makes surface treatment a reasonably promising field for promoting combustion near surfaces.

CONCLUSION

Summary. From the study of the mechanism of combustion in the Bunsen burner, it appeared that the critical characteristic of flow for stable flames was the velocity gradient between the ignited and unignited gas. An experiment was then performed to determine whether three differently shaped flame holders would give the same performance if the velocity gradient were held constant. The flat and concave downstream surfaces gave identical results; the hemispherical surface gave poorer performance, but it was determined that for this case the velocity gradient had not been held constant, and an explanation of the performance involving the movement of the point of separation of flow has been given that is in accord with the theory of velocity gradients.

A picture of the flame holder mechanism as determined from this investigation is given in review. A turbulent region is created downstream from the flame holder where combustion is promoted by the low velocity and turbulence and inhibited in the layers adjacent to the flame holder by the quenching effect of the metal wall. If the gradient of velocity between the burning turbulent region and the outside free stream is not too great the flame will spread radially producing an inverted cone whose vertex is twice the angle whose tangent is the burning velocity divided by the gas velocity. The burning velocity depends primarily upon mixture, proximity to a wall, turbulence, and secondarily upon preheating and other variables. The combustion reaction is completed in a very short space, less than 0.2 inches in this experiment, and a very high temperature gradient exists through this space.

The flame reaction creates a back pressure which retards the flow and causes the stream to diverge ahead of the flame. The total pressure downstream from the flame is lower than that above it by an unknown amount and for reasons not clearly known.

Limitations of the Work and Suggestions for Further Investigation.

The limitations of this study are manifold in the respect that many of the important variables could not be more thoroughly investigated due to lack of time or equipment. Primary among the slighted factors are thorough and accurate temperature and pressure traverses, without which the complete picture of the flame mechanism can never be worked out. A larger flame holder would have simplified making these traverses since small disturbances of the flame structure would be less important in a large flame, but the high temperatures constitute an unavoidable problem. A thorough spectroscopic mapping of the temperature would be far superior to any thermocouple measurements since there would be no disturbance to the flame and no surface effect. Pressure traverses could be made with a very fine steel impact tube. With a larger flame holder also the schlieren method may tell more since high enough velocities might be obtained with a larger device to enable the schlieren to pick up the exact flow pattern around the end of the flame holder. It might have been revealing to have the remainder of the mixture-versus-flow at blow-off curves, but for comparing the three flame holders it does not seem of primary importance. A thorough study of the back pressure of the flame as a function of the flow rate and burning rate could be made

fairly simply if time permitted, and should be very informative.

One of the things most needed is a means of tracing out the streamlines of flow through the whole region in a manner similar to the mapping of the Bunsen flame by Lewis and von Elbe. During the present investigation repeated attempts were made to record photographically the tracks of illuminated particles of talcum powder and magnesium carbonate; and, although a light source of approximately four million lumens was placed within six inches of the stream, the paths could not be recorded with available photographic equipment at the velocities of interest in the investigation. It would be a natural next step to build a larger flame holder capable of burning at higher velocities in order to see if the flat and concave surfaces give the same results at higher velocities. The aerodynamic effect of the design of the upstream surface upon velocity gradient and the resulting performance should be investigated. Also the effect of the type of flow in the stream upon the flame holder should be studied. For instance, is a thicker boundary layer and better performance obtained when the flame holder is placed in a diverging stream rather of a constant area or a converging stream? What is the effect of introducing fuel into the turbulent regions in the wake of the flame holder rather than upstream from it? Obviously, the problem of the theory of the flame holder has only been opened in this investigation.

ADDENDUM NO. 1

Further evidence that the back flow in the turbulent region of the concave flame holder did not circulate through the concavity was obtained subsequent to the experiments previously described from the water table designed and constructed at the Rensselaer Polytechnic Institute by Lieutenant Commander Robert A. Thompson, U.S.N., and Lieutenant Commander Howard G. Smelin, U.S.N. For a detailed discussion of the analogy of water flow to air flow see their paper "The Theory, Construction, and Application of the Water Table." The flow on this table corresponds to the flow of a gas having a ratio of specific heats equal to 2.0, and due to surface foam from the wetting agent gives a wonderful visual picture of almost any desired flow pattern.

Using a wood model of the same shape as the cross section of the concave flame holder earlier investigated, flows ranging from a Mach number of practically zero to a Mach number of approximately three were observed; and it was found that the main turbulent eddies did not enter the concavity at any time. This corresponds to flow without ignition around this flame holder. At low Mach numbers, below about seven or eight tenths, the eddies in the wake appeared very similar to those behind a flat surface; and at higher Mach numbers the eddies flattened along a very flat straight line perpendicular to the main stream from one downstream tip to the other. The angle at which the eddy current merged with the free stream was at all times very nearly ninety degrees. The flow was practically identical with the

flow previously described as probable and pictured in Figure 10. Slight diffusion into the "stagnant region" was observed, but the main flow did not circulate upstream from the tips of the flame holder.

This means that the concave flame holder could be expected to give practically identical results with the flat flame holder over all ranges of stream velocity. The only significant factor that might change this expectation is that the concavity offers a larger low velocity turbulent region to retain flames than a flat ended flame holder of the same diameter; but the effect of this factor is not known.

AIR FLOW

Record of Δh in inches of water across metering orifice at instant of blow-off with lean mixtures

Fuel Pressure = 2.5 lb./sq.in.

	Concave	Round	Flat
	0.13	0.13	0.13
	0.13	0.13	0.14
	0.14	0.13	0.13
Total	0.40	0.39	0.40
Avg.	0.133	0.13	0.133

Fuel Pressure = 4.75 lb./sq.in.

	Concave		Round		Flat
	0.20		0.18		0.19
	0.20		0.18		0.20
	0.21		0.18		0.20
	0.20		0.19		0.20
	0.18		0.19		0.20
	0.20		0.20	Total	0.99
Total	1.19		0.20		
			0.19	Avg.	0.198
Avg.	0.198		0.18		
			0.19		
		Total	1.88		
		Avg.	0.188		

Fuel Pressure = 8.75 lb./sq.in.

Concave		Round		Flat
0.28		0.27		0.30
0.28		0.27		0.29
0.28		0.24		0.29
0.29		0.27		0.28
0.30		0.28		0.29
0.28	Total	1.33		0.29
Total 1.71				0.28
	Avg.	0.266		0.28
Avg. 0.285			Total	2.30
			Avg.	0.287

Fuel Pressure = 15 lb./sq.in.

Concave		Round		Flat
0.45		0.42		0.43
0.45		0.41		0.47
0.44		0.42		0.45
0.46		0.42		0.45
Total 1.80		0.43		0.45
	Total	2.10		0.45
Avg. 0.45			Total	2.70
	Avg.	0.42		
			Avg.	0.45

Fuel Pressure = 24 lb./sq.in.

Concave		Round		Flat
0.75		0.63		0.75
0.83		0.68		0.79
0.79		0.65		0.79
0.78		0.65		0.77
Total 3.15		0.64	Total	3.10
		0.65		
Avg. 0.787	Total	3.90	Avg.	0.775
	Avg.	0.65		

Fuel Pressure = 30 lb./sq.in.

	Concave	Round	Flat
	0.97	0.85	0.94
	1.03	0.85	1.10
	1.00	0.85	0.97
Total	3.00	2.55	3.01
Avg.	1.00	0.85	1.003

Record of Δh in inches of water across metering orifice at instant of blow-off with rich mixtures

Fuel Pressure = 2.5 lb./sq.in. No reading

Fuel Pressure = 5 lb./sq.in. No reading

Fuel Pressure = 8 lb./sq.in.

	Concave		Round		Flat
	0.060		0.075		0.065
	0.065		0.075		0.065
	0.070		0.075		0.065
	0.065		0.075	Total	0.195
Total	0.260		0.300		
				Avg.	0.065
Avg.	0.065		0.075		

Fuel Pressure = 15 lb./sq.in.

	Concave		Round		Flat
	0.11		0.115		0.11
	0.10		0.105		0.10
	0.10		0.110		0.10
	0.10	Total	0.320		0.10
Total	0.41			Total	0.41
		Avg.	0.110		
Avg.	0.102			Avg.	0.102

Fuel Pressure = 20 lb./sq.in.

	Concave	Round	Flat
	0.15	0.15	0.15
	0.15	0.15	0.145
	0.15	0.15	0.155
Total	0.45	0.45	0.45
Avg.	0.15	0.15	0.15

Fuel Pressure = 24 lb./sq.in.

	Concave	Round		Flat
	0.190	0.23		0.195
	0.200	0.22		0.19
	0.195	0.215		0.19
	0.190	0.23	Total	0.575
Total	0.775	0.895		
			Avg.	0.1916
Avg.	0.193	0.224		

Fuel Pressure = 30 lb./sq.in.

	Concave		Round	Flat
	0.29		0.36	0.29
	0.29		0.36	0.29
	0.29		0.355	0.29
Total	0.87		0.365	0.29
		Total	1.44	1.16
Avg.	0.29			
		Avg.	0.36	0.29

Fuel Pressure = 35 lb./sq.in.

	Concave		Round		Flat
	0.375		0.53		
	0.385		0.525		0.39
	0.38	Total	1.055		0.37
	0.38				0.38
Total	1.52	Avg.	0.5275	Total	1.14
Avg.	0.38			Avg.	0.38

FUEL FLOW CALIBRATION

Record of times required for one pound of fuel to flow through burner for a given fuel pressure in the fuel line.

Fuel Pressure = 40 lb./sq.in.

min.	sec.	seconds
4	47	287
4	45	285
4	45	285
4	50	290
	Total	1147
	Avg.	286.7

w/sec = $\frac{1}{286.7}$ = 0.00348

Fuel Pressure = 35 lb./sq.in.

min.	sec.	seconds
5	08	308
5	06	306
5	12	312
5	10	310
	Total	1236
	Avg.	309

w/sec = $\frac{1}{309}$ = 0.003235

Fuel Pressure = 30 lb./sq.in.

min.	sec.	seconds
6	07	367
6	10	370
6	10	370
	Total	1107
	Avg.	369

w/sec = $\frac{1}{369}$ = 0.00271

Fuel Pressure = 24 lb./sq.in.

min.	sec.		seconds
6	40		400
7	08		428
7	00		420
6	48		408
		Total	1656
		Avg.	414

w/sec = $\frac{1}{414}$ = 0.002415

Fuel Pressure = 20 lb./sq.in.

min.	sec.		seconds
8	35		515
8	05		485
8	03		483
8	37		517
		Total	2000
		Avg.	500

w/sec = $\frac{1}{500}$ = 0.0020

Fuel Pressure = 15 lb./sq.in.

min.	sec.		seconds
9	55		595
10	05		605
10	01		601
		Total	1801
		Avg.	600

w/sec = $\frac{1}{600}$ = 0.00166

Record of times required for one half pound of fuel to flow through burner for a given fuel pressure in the fuel line.

Fuel Pressure = 8.75 lb./sq.in.

min.	sec.	seconds
6	07	367
6	05	365
6	10	370
	Total	1102
	Avg.	367.3

$w/sec = \frac{0.5}{367.3} = 0.001361$

Fuel Pressure = 4.5 lb./sq.in.

min.	sec.	seconds
7	46	466
7	50	470
7	45	465
7	40	460
	Total	1861
	Avg.	465.2

$w/sec = \frac{0.5}{465.2} = 0.001073$

Fuel Pressure = 2 lb./sq.in.

min.	sec.	seconds
8	47	527
10	05	605
	Total	1132
	Avg.	566

$w/sec = \frac{0.5}{566} = 0.000883$

Appendix B

Computations

I Air Flow

Refer to "History of Orifice Meters and the Calibration, Construction, and Operation of Orifices for Metering - 1935," published by the A.S.M.E. Also to Marks Handbook.

The expression for the volume rate of flow is

$$Q = Y E C A \sqrt{2 g h}$$

where Q = $ft.^3/sec.$

Y = compressibility

E = velocity of approach factor

C = coefficient of discharge

A = throat area in $ft.^3$

h = differential head in ft. of measured fluid (conditions at upstream tap)

Orifice diameter = 1.531 inches

Pipe diameter = 3.00 inches

$$\beta = \frac{\text{orifice diameter}}{\text{pipe diameter}} = \frac{1.531}{3.000} = 0.5103$$

Assuming that the average velocity during the experiment will be 75 ft./sec. and that the density and viscosity of the combustion

mixture approximate the values for air,

$$R_2 = \frac{\rho v l}{\mu} = \frac{.07651 \times 75 \times 1.531}{126 \times 10^{-7} \times 12} = 0.0562 \times 10^6$$

For $\beta = 0.5103$ and $R_2 = 0.0562 \times 10^6$, from the table page 45 of the A.S.M.E. publication,

$$E = MC = 0.624 \text{ for the orifice used.}$$

The pressure differential across the meter was approximately one inch of water, hence

$$\frac{P_{upstream}}{P_{downstream}} \cong 1.0$$

and therefore $Y = 1.0$

Substituting these values into the equation for Q

$$Q = 0.624 \times \frac{1.581}{144} \times 8.03 \sqrt{\Delta h}$$

$$Q = 0.0441 \sqrt{\Delta h}$$

To convert Δh in inches of water to feet of air, multiply by

$$\frac{62.4}{12 \times 0.07651} = 68$$

or $$\Delta h_{in.H_2O} \times 68 = \Delta h_{ft.air}$$

To convert Q_{air} = ft.^{3}/sec. to w_g/sec. = lb./sec. multiply by the density in lb./ft.^{3} = 0.07651

$$\frac{Q_{air}}{0.07651} = w_g/\text{sec.}$$

To convert w_g/sec. to Q_{fuel} divide by the fuel density in lb./ft.^{3} = 1.56 x 0.07651 = 0.1195

$$\frac{w_g/\text{sec.}}{0.1195} = Q_{fuel}$$

The computations are shown in the following tables.

Tabulation of Computations for the Round-end Rod

Object: to obtain values of Q at blow-off for various values of w_f/w_a, fuel-to-air ratio. Explanation of symbols and method of computation is in foregoing pages.

Lean Mixtures

P_f	Δh	Δh		Q_{air}	Q_{fuel}	Q_{total}
lb./in.^{2}	in.H_2O	ft.air	$\sqrt{\Delta h}$	ft.^{3}/sec.	ft.^{3}/sec.	ft.^{3}/sec.
2.5					0.00712	
4.75	0.188	12.3	3.51	0.225	0.00898	0.233
8.75	0.266	18.1	4.24	0.272	0.01146	0.282
15.0	0.42	28.6	5.35	0.343	0.0148	0.358
24.0	0.65	44.2	6.65	0.426	0.0198	0.446
30.0	0.85	57.8	7.60	0.487	0.0231	0.510

P_f	w/sec	w/sec	w_f/w_a
lb./in.^{2}	air	fuel	
2.5		0.00085	
4.75	0.01725	0.001073	0.0622
8.75	0.02085	0.001370	0.0657
15.0	0.0263	0.00177	0.0672
24.0	0.0326	0.00237	0.0727
30.0	0.0373	0.00276	0.0740

Rich Mixtures

P_f	Δh	Δh		Q_{air}	Q_{fuel}	Q_{total}
lb./in.^{2}	in.H_2O	ft.air	$\sqrt{\Delta h}$	ft.^{3}/sec.	ft.^{3}/sec.	ft.^{3}/sec.
8.0	0.075	5.10	2.26	0.145	0.01095	0.156
15.0	0.110	7.48	2.72	0.168	0.0148	0.1828
20.0	0.150	10.2	3.16	0.2045	0.0176	0.2221
24.0	0.247	16.8	4.1	0.263	0.0198	0.2828
30.0	0.360	24.5	4.95	0.317	0.0231	0.3401
35.0	0.5275	35.9	5.99	0.384	0.0259	0.4099

P_f	w/sec	w/sec	
			w_f/w_a
lb./in.^{2}	air	fuel	
8.0	0.0111	0.00132	0.119
15.0	0.0140	0.00177	0.1265
20.0	0.01565	0.0021	0.1341
24.0	0.0215	0.00237	0.1177
30.0	0.0243	0.00276	0.1135
35.0	0.0294	0.0031	0.1055

Tabulation of Computations for the Flat-end Rod

Object: to obtain values of Q at blow-off for various values of w_f/w_a, fuel-to-air ratio. Explanation of symbols and method of computation is in foregoing pages.

Lean Mixtures

P_f	Δh	Δh		Q_{air}	Q_{fuel}	Q_{total}
lb./in.^{2}	in.H_2O	ft.air	$\sqrt{\Delta h}$	ft.^{3}/sec.	ft.^{3}/sec.	ft.^{3}/sec.
2.5	0.133	9.04	3.01	0.193	0.00712	
4.75	0.198	13.48	3.67	0.235	0.00898	0.243
8.75	0.287	19.55	4.42	0.283	0.01146	0.294
15.0	0.45	30.60	5.53	0.354	0.0148	0.358
24.0	0.775	52.70	7.26	0.465	0.0198	0.485
30.0	1.003	68.20	8.26	0.530	0.0231	0.553

P_f	w/sec	w/sec	w_f/w_a
lb./in.^{2}	air	fuel	
2.5	0.01478	0.00085	
4.75	0.0180	0.001073	0.0596
8.75	0.02165	0.001370	0.0633
15.0	0.0271	0.00177	0.0672
24.0	0.0356	0.00237	0.0666
30.0	0.0406	0.00276	0.0680

Rich Mixtures

P_f lb./in.^{2}	Δh in.H_2O	Δh ft.air	$\sqrt{\Delta h}$	Q_{air} ft.^{3}/sec.	Q_{fuel} ft.^{3}/sec.	Q_{total} ft.^{3}/sec.
15.0	0.103	7.0	2.545	0.163	0.0148	0.1778
20.0	0.150	10.2	3.19	0.2045	0.0176	0.2221
24.0	0.1916	13.02	3.61	0.231	0.0198	0.2508
30.0	0.29	19.7	4.44	0.2845	0.0231	0.3076
35.0	0.38	25.85	5.09	0.326	0.0259	0.3519

P_f lb./in.^{2}	w/sec air	w/sec fuel	w_f/w_a
15.0	0.01248	0.00177	0.142
20.0	0.01565	0.0021	0.1341
24.0	0.0177	0.00237	0.1340
30.0	0.0218	0.00276	0.1265
35.0	0.025	0.0031	0.124

Tabulation of Computations for Concave-end Rod

Object: to obtain values of Q at blow-off for various values of w_f/w_a, fuel-to-air ratio. Explanation of symbols and method of computation is in foregoing pages.

Lean Mixtures

P_f	Δh	Δh		Q_{air}	Q_{fuel}	Q_{total}
lb./in.^{2}	in.H_2O	ft. air	$\sqrt{\Delta h}$	ft.^{3}/sec.	ft.^{3}/sec.	ft.^{3}/sec.
2.5					0.00712	
4.75	0.192	13.10	3.62	0.232	0.00898	0.240
8.75	0.285	19.3	4.40	0.282	0.01146	0.293
15.0	0.45	30.6	5.53	0.354	0.0148	0.369
24.0	0.787	53.5	7.31	0.469	0.0198	0.489
30.0	1.0	68.0	8.25	0.528	0.0231	0.551

P_f	w/sec	w/sec	w_f/w_a
lb./in.^{2}	air	fuel	
2.5		0.00085	
4.75	0.0178	0.001073	0.0602
8.75	0.0216	0.001370	0.0634
15.0	0.0271	0.00177	0.0653
24.0	0.03745	0.00237	0.0633
30.0	0.0404	0.00276	0.0683

Rich Mixtures

P_f	Δh	Δh		Q_{air}	Q_{fuel}	Q_{total}
lb./in.^{2}	in.H_2O	ft.air	$\sqrt{\Delta h}$	ft.^{3}/sec.	ft.^{3}/sec.	ft.^{3}/sec.
15.0	0.102	6.94	2.535	0.1625	0.0148	0.1773
20.0	0.150	10.20	3.190	0.2045	0.0176	0.2221
24.0	0.193	13.11	3.620	0.232	0.0198	0.2498
30.0	0.290	19.70	4.44	0.284	0.0231	0.3076
35.0	0.380	25.85	5.09	0.326	0.0259	0.3519

P_f	w/sec	w/sec	w_f/w_a
lb./in.^{2}	air	fuel	
15.0	0.01244	0.00177	0.1421
20.0	0.01565	0.0021	0.1341
24.0	0.0178	0.00237	0.1332
30.0	0.0218	0.00276	0.1265
35.0	0.025	0.0031	0.124

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